Frontier Expansion and Resource-Based Development with Spillovers

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Revised Draft
July 12, 2004

Paper for the NBER Summer Institute 2004 Workshop on Public Policy and the Environment, Cambridge, Massachusetts, August 2-3, 2004

Acknowledgements: I would thank Don Fullerton and Gavin Wright for helpful comments on previous versions of this paper.

Abstract

Historical evidence suggests that there are three conditions for "successful" resource-based development in a small open economy: exogenous technological change in resource use, complete integration between a frontier, resource-extracting sector and a mainstay sector and knowledge spillovers. The following paper develops a model of frontier resource exploitation to demonstrate how these three conditions can lead to sustained growth. Several results emerge. First, as long as some frontier resource is available, it is always optimal for the economy to extract and use the resource. Second, once the frontier is "closed" and all resource extraction stops, it is still possible to generate sustained growth in the small open economy, as knowledge spillovers prevent any diminishing returns to capital. Finally, if frontier resources are exploited at the maximum rate or when the frontier is closed, a subsidy is necessary because the presence of an economy-wide knowledge spillover means that the private return to capital investment is lower than the social return.

Keywords: developing economies, frontier expansion, knowledge spillovers, resource-based development, small open economy.

JEL classification: O13, O41, Q32, Q33.

Introduction

Historically, "frontier expansion" has been a major part of economic development (Cipolla 1976; di Tella 1983; North and Thomas 1973; Toynbee 1976; Webb 1964). Such frontier-based economic development is characterized by a pattern of capital investment, technological innovation and social and economic institutions dependent on "opening up" new frontiers of natural resources once existing ones have been "closed" and exhausted (di Tella 1982; Findlay 1995; Findlay and Lundahl 1994). Although in the past frontier expansion may have been associated with successful resource-based development, the "resource curse" literature suggests that exploiting such resource "windfalls" is less beneficial for open economies today (Auty 2001; Stevens 2003). For example, cross-country empirical analysis indicates that in recent decades resource-abundant countries - i.e. countries with a high ratio of natural resource exports to GDP - have tended to grow less rapidly than countries that are relatively resource poor (Rodríguez and Sachs 1999; Sachs and Warner 1997 and 2001).

However, under certain conditions, frontier expansion in a small open economy can be associated with successful resource-based development. There are clearly historical precedents for such a development path. For example, it has been argued that the origins of rapid industrial and economic expansion in the US over 1879-1940 were strongly linked to the exploitation of abundant non-reproducible natural resources, particularly energy and mineral resources (Romer 1996; Wright 1990). Other examples of successful mineral-based development have been cited for today's economies (Davis 1995; Wright and Czelusta 2002). In the developing world, most prominent have been the mineral-led booms in the 1990s in Peru, Brazil and Chile, although Davis (1995) identifies up to 22 mineral-based developing economies who appear to have fared comparatively well compared to other developing countries.

Recent reviews of successful resource-based development, both past and present, have pointed to a number of key features critical to that success (David and Wright 1997; Wright and Czelusta 2002).

First, the given natural resource endowment of a country must be continuously expanded through a process of *country-specific knowledge in the resource extraction sector*. As argued by Wright and Czelusta (2002, pp. 29 and 31): "From the standpoint of development policy, a crucial aspect of the process is the role of country-specific knowledge. Although the deep scientific bases for progress are undoubtedly global, it is in the nature of geology that locationspecific knowledge continues to be important….the experience of the 1970s stands in marked contrast to the 1990s, when mineral production steadily expanded primarily as a result of purposeful exploration and ongoing advances in the technologies of search, extraction, refining, and utilization; in other words by a process of learning."

Second, there must be *strong linkages between the resource and other, more dynamic economic sectors (i.e., manufacturing)*. "Not only was the USA the world's leading mineral economy in the very historical period during which the country became the world leader in manufacturing (roughly from 1890 to 1910); but linkages and complementarities to the resource sector were vital in the broader story of American economic success….Nearly all major US manufactured goods were closely linked to the resource economy in one way or another: petroleum products, primary copper, meat packing and poultry, steel works and rolling mills, coal mining, vegetable oils, grain mill products, sawmill products, and so on" (Wright and Czelusta 2002, pp. 3-5).

Third, there must be *substantial knowledge spillovers* arising from the extraction and industrial use of resources in the economy. For example, David and Wright (1997) suggest that the rise of the American minerals economy can be attributed to the infrastructure of public scientific knowledge, mining education and the "ethos of exploration". This in turn created knowledge spillovers across firms and "the components of successful modern-regimes of knowledge-based economic growth. In essential respects, the minerals economy was an integral part of the emerging knowledge-based economy of the twentieth century….increasing returns were manifest at the national level, with important consequences for American industrialization and world economic leadership" (David and Wright 1997, pp. 240-241).[1]

However, there are two important caveats attached to the above conditions for successful resource-based development.

First, all of the past and present examples of development with the above three features are clearly based largely on minerals-based development (David and Wright 1997; Wright and Czelusta 2002). There is little evidence to date that a small open economy dependent on frontier agricultural land expansion is likely to foster the above conditions for successful resource-based

[1] Wright and Czelusta (2002, p. 17) cite the specific example of the development of the US petrochemical industry to illustrate the economic importance of knowledge spillovers: "Progress in petrochemicals is an example of new technology built on resource-based heritage. It may also be considered a return to scale at the industry level, because the search for by-products was an outgrowth of the vast American enterprise of petroleum refining."

development.[2] In fact, there is some evidence that agricultural-based development based on land expansion may be negatively correlated with economic growth and development (Barbier 2003 and 2004; Stijns 2001).

Second, the existence of policy and market failures in the resource sector, such as rent-seeking behavior and corruption or open-access resource exploitation, will mitigate against successful resource-based development. Unfortunately, it is well documented that resource sectors in many developing countries are prone to problems of rent-seeking and corruption, thus ensuring that natural resource assets, including land, are not being managed efficiently or sustainably (Ascher 1999; Karl 1997; Tornell and Lane 2001; Torvik 2002).[3] Several studies have also noted the rent-dissipation effect of poorly defined property rights, including the breakdown of traditional common property rights regimes, in developing countries (Alston *et al.* 1999; Baland and Plateau 1996; Bromley 1989 and 1991; Deacon 1999; Ostrom 1990).

These two caveats aside, there is nevertheless an important issue to address here: Can frontier resource exploitation ever be compatible with successful resource-based development in a small open economy, or is economic growth limited to a short-run economic "boom" that occurs only as long as new frontier resources are available to exploit? A previous analysis of frontier expansion and economic development has illustrated the latter outcome (Barbier 2005). Initially, it is always optimal for the economy to choose the maximum rate of frontier expansion, and thus ensure an immediate economic boom. However, an eventual economic decline is unavoidable, regardless of whether abundant or relatively small frontier reserves are available to exploit.

However, as the following paper demonstrates, a "boom and bust" frontier-based development path is not necessarily inevitable. Frontier expansion in a small open economy can lead to sustained long-run growth, provided the three conditions for "successful" resource-based development identified above are present in the economy: 1) exogenous technological change in

[2] The one historical exception might be the "wheat boom" in 19th century Canada that led to "staples-based" export development. See Watkins (1963).

[3] There is also an obvious link between rent-seeking activities in frontier areas and the lack of government enforcement of efficient regulation of these activities For example, Ascher (1999, p.268) points out: "The weak capacity of the government to enforce natural-resource regulations and guard against illegal exploitation is an obvious factor in many of the cases reviewed. In every case of land and forest use, illegal extraction and failure to abide by conservation regulations reduce the costs to the resource exploiter and induce overexploitation, while failing to make the exploiter internalize the costs of resource depletion and pollution."

resource use, 2) complete integration between the frontier and mainstay sectors, and 3) economy-wide knowledge spillovers. Moreover, to avoid the problems posed by the two "caveats" identified above, we will assume that the frontier resource comprises mineral resources and that these resources are extracted efficiently, i.e. there is no rent-seeking, corruption or open access behavior.

Several important results emerge from the model. First, the availability of a "frontier" resource remains a pervasive influence on the economy. As long as some frontier resource is available, it is always optimal for the economy to extract and use the resource. The first condition for successful resource-based development, exogenous technological change in resource use, does help to extend the life of the available frontier resource stock. However, this condition on its own is not sufficient to prevent economic growth to end once the frontier is fully exploited, or "closed". But if the resource output from the frontier serves as an input into the mainstay production sector, then this ensures that frontier resource exploitation will contribute to some capital investment by entrepreneurs in the latter sector. More importantly, the presence of knowledge spillovers means that capital accumulation in that sector contributes to overall innovation in the economy. It therefore follows that, once the frontier is "closed" and all resource extraction stops, it is still possible to generate sustained growth in the small open economy, as knowledge spillovers prevent any diminishing returns to capital. In essence, the economy has transitioned from a frontier resource-dependent economy to a fully "modernized" capital-labor economy with knowledge spillovers leading to endogenous growth (Arrow 1962; Romer 1986).

Finally, if frontier resources are exploited at the maximum rate or when the frontier is closed, we find that a subsidy is necessary because the presence of an economy-wide knowledge spillover means that the private return to capital investment is lower than the social return. If the government subsidizes the contribution of capital to firms' production, the difference between social and private returns to capital in the economy could be eliminated, and the growth rate generated by the decentralized economy would also be socially optimal. Unfortunately, government subsidies are also ripe for abuse. There is plenty of evidence that government investment and subsidies in resource sectors are not aimed at promoting knowledge spillovers but encouraging problems of rent-seeking and corruption, including in mineral-based economies (Ascher 1999; Barbier 2003 and 2004; Karl 1997; López 2003).

The Small Open Economy Model

The small open economy is assumed to comprise an integrated frontier and mainstay sector. The frontier sector consists of extractive industries that are dependent on one or more mineral resources, which are ultimately limited in supply.[4] Although clearly heterogeneous, these available "frontier resources" will be treated as an aggregate, homogeneous stock. Equally, the extractive industries and economic uses of these resources will be aggregated into a single sectoral output.

Although mainstay economic activities can be considered separate from the frontier sector, the two sectors are fully linked. That is, the output produced through exploiting frontier "reserves" is an intermediate input into all mainstay production activities. The latter activities can be considered the manufacturing and industrial processing industries of the economy that utilize the "raw material" frontier resources as inputs, e.g. petrochemical, mineral processing and steel industries.

Thus, at some initial time $t = 0$, the frontier sector of the economy is assumed to be endowed with a given stock of natural resources, F_0, which acts as a "reserve" that can be potentially tapped through the rate of extraction, N. Hence, in the following model, the process of "frontier expansion" is essentially marked by the continual use and depletion of the fixed stock of frontier resources, F_0. To sharpen the analysis, we will not include explicitly a cost of frontier resource conversion but postulate that the existence of institutional, geographical and economic constraints limits the maximum amount of frontier resource exploitation at any time t to $\overline{N}$.[5] Over a finite planning horizon, T, it follows that

$$F_0 \geq \int_0^T N\,dt, \quad 0 \leq N \leq \overline{N}, \quad F_0 = F(0) \tag{1}$$

[4] Historically, old growth forests that were discovered in frontier regions were often "mined" in a similar fashion as non-renewable resources. This practice continues with many old growth forests in temperate and tropical frontier regions today, such as Siberia, Central Africa, South East Asia and Latin America.

[5] Many frontier resources are located far from population centers, and thus the rate at which these resources may be profitably converted or exploited may be constrained by distance to market and accessibility. Following the approach of North (1990), who defines institutions as "humanly devised constraints that shape human interaction" and which "affect the performance of the economy by their effect on the costs of exchange and production," recent studies have also explored the impact on frontier resource extraction and land conversion of institutional factors, such as land use conflict, security of ownership or property rights, political stability, and the "rule of law" (e.g. Alston *et al.* 2000; Barbier 2002; Deacon 1999). Bohn and Deacon (2002) illustrate that reduction of ownership risk is also fundamental to reducing over-exploitation of a variety of natural resources.

In our model it will be convenient to express the rate of resource extraction in per capita terms. We consider aggregate labor supply, L, and population in the economy to be the same, and we assume that both are growing at the exogenous rate θ. We make the standard assumption that the initial stock of labor, L_0, is normalized to one. Utilizing the relationship $N = ne^{\theta t}$, condition (1) can be re-written as

$$F_0 \geq \int_0^T ne^{\theta t}\, dt, \quad 0 \leq n \leq \bar{n}, \quad F_0 = F(0) \tag{2}$$

where $\bar{n}$ is the maximum per capita amount of frontier resource conversion that can occur at any time t. Since from labor supply grows exogenously, the maximum conversion rate, $\bar{n}$, must decline over time.

Firm i in the mainstay sector combines natural resources and other inputs to produce output, M_i

$$M_i = M(K_i, N_i, B_i L_i) \tag{3}$$

where K_i is the capital stock and L_i is the labor employed by the firm, and B_i is the index of knowledge available to the firm.

We make the classic "knowledge spillover" assumptions concerning productivity growth in the mainstay sector (Arrow 1962; Romer 1986). First, learning-by-doing innovation works through each firm's investment. An increase in a firm's capital stock leads to a parallel increase in its stock of knowledge, B_i. Second, each firm's knowledge is a public good that any other firm can access at zero cost. In other words, once discovered, any new technology spills over instantly across the whole mainstay sector. This assumption implies that the change in each firm's technology term, dB_i/dt, corresponds to the overall learning in the mainstay sector and is therefore proportional to the change in the aggregate capital stock, dK/dt.[6] These assumptions allow B_i to be replaced by K in (3), so that $M_i = M(K_i, N_i, KL_i)$.

The second technological change occurs in resource production. That is, we assume that exogenous technological change contributes to an effective increase in the amount of resources extracted and available to each mainstay firm. In essence, this source of technological innovation represents increased knowledge in the frontier sector that essentially extends the life

[6] The specification that all discoveries are unintended by-products of investment and that these discoveries immediately become common knowledge allows the framework of perfect competition to be retained for the mainstay sector, although as we see below the outcomes turn out not to be Pareto optimal.

of the available frontier resource stock, F. Thus, if N is the aggregate amount of "raw" resource stock extracted at any time t from the frontier resource, the effective amount of resource available for use by any mainstay firm is $a(t)N_i$ with $a(t) = a_0 e^{\alpha t}$.

The above assumptions allow the production function for each firm i in the mainstay sector to be written in intensive form as

$$m_i = m(k_i, n_i, K; a(t)) = a(t)n_i + f(k_i, K), \quad m_i = \frac{M_i}{L_i},\ k_i = \frac{K_i}{L_i},\ n_i = \frac{N_i}{L_i}. \tag{4}$$

To facilitate our analysis, we separate the spillover investment effects from the exogenous resource technological change effects on mainstay production. If k and l_i are constant, then each firm faces diminishing returns to k_i as in a standard neoclassical production function. However, if each producer expands $k_{i,}$, then K rises accordingly across the entire mainstay sector and provides a spillover benefit that raises the productivity of all firms. Moreover, $f(\bullet)$, which represents the function for the contribution of capital to mainstay production, is homogeneous of degree one in k_i and K for given l_i. This implies that there are constant returns to capital at the social level, when k_i and K expand together for a fixed l. Technological change in resource use implies that, for each firm, the marginal productivity of n_i is not diminishing but grows at the exogenous rate α.

A firm's profit function can be written as

$$\pi_i = L_i\left[a(t)n_i + f(k_i, K) - w^N n_i - w - (r + \omega)k_i\right] \tag{5}$$

where w^N is the rental price of the frontier resource, w is the wage rate, $r + \omega$ is the rental price of capital (i.e., the interest rate, r, plus capital depreciation, ω), and output price is normalized to one. Each perfectly competitive firm takes these prices as given. In addition, each firm is small enough to neglect its own contribution to the aggregate capital stock and therefore treats K as given.

Profit maximization and the zero profit condition imply

$$\begin{aligned} \frac{\partial \pi_i}{\partial k_i} &= \frac{\partial m_i}{\partial k_i} = f_1(k_i, K) = r + \omega \\ \frac{\partial \pi_i}{\partial n_i} &= \frac{\partial m_i}{\partial n_i} = a(t) = w^N \\ \frac{\partial \pi_i}{\partial L_i} &= \frac{\partial M_i}{\partial L_i} = f(k_i, K) - k_i f_1(k_i, K) = w \end{aligned} \tag{6}$$

In equilibrium, all firms make the same choices so that $k_i = k$, $n_i = n$, $m_i = m$ and $K = kL$. Since $f(\bullet)$ is homogeneous of degree one in k_i and K, we can write the average product of capital as

$$\frac{m}{k} = \frac{a(t)n + f(k,K)}{k} = \frac{a(t)n}{k} + \tilde{f}\left(\frac{K}{k}\right) = \frac{a(t)n}{k} + \tilde{f}(L) \tag{7}$$

where $\tilde{f}(L)$ is the function for the average contribution of capital to mainstay production.[7] This function is invariant with respect to k and increases with L but at a diminishing rate, $\tilde{f}''(L) < 0$. It follows from (7)

$$m = a(t)n + \tilde{f}(L)k \qquad \text{and} \qquad \frac{\partial m}{\partial k} = \tilde{f}(L) - L\tilde{f}'(L). \tag{8}$$

Thus the private marginal product of capital is invariant with k and n, increasing in L and is less than the average product.

Per capita output from the mainstay sector may be used for domestic consumption, c, or exported, x. To focus the analysis, we will treat domestic consumption and exports as homogeneous commodities. Let $q = c + x$ be defined as aggregate consumption, both domestic and foreign, of the economy's total output. If households own all the assets in the economy, and s is the net assets per person measured in real terms (i.e. in terms of units of consumables), then real wealth per capita in the economy will increase according to

$$\dot{s} = rs + w + w^N n - \theta s - q. \tag{9}$$

If all the capital stock in the economy is owned by households, then $s=k$. Substituting this condition and (6) into the budget constraint (9) yields

$$\begin{aligned} \dot{k} &= [f_1(k,K) - \omega]k + f(k,K) - f_1(k,K)k + a(t)n - \theta k - q \\ &= \tilde{f}(L)k + a(t)n - (\omega + \theta)k - q \end{aligned} \tag{10}$$

In exchange for its exports, the economy imports a consumption good, z. As the country is a small open economy, the terms of trade are fixed and defined as $p = p^x/p^z$. Thus the balance of trade condition for the economy is

$$px = z \tag{11}$$

[7] It is clear from (7) that the average contribution of capital to production, $\tilde{f}(L)$, is not the same as the average product of capital in mainstay production. That is, $\tilde{f}(L) = m/k$ only if there is no resource extraction, i.e. $n = 0$.

Finally, all consumers in the economy share identical preferences over the finite time horizon [0, T] given by

$$W = \int_0^T [\beta \log(c) + \log(z)] e^{-\rho t} dt + \psi_T k(T) e^{-\rho T}, \;\; \rho = \delta - \theta, \; \beta > 0, \tag{12}$$

where δ is the discount rate and ψ_T is the scrap value of the terminal capital stock, $k(T)$.

The Social Planner's Problem

Any social planner in the small open economy will recognize that each firm's increase in its capital stock adds to the aggregate capital stock, thus contributing to the productivity of all other firms in the economy. This implies that the social planner will take into account, or internalizes, the knowledge spillovers across all firms. The planner's objective is therefore to maximize the welfare function (12) over finite time T with respect to aggregate per capita consumption, q, exports, x, and frontier resource exploitation, n, subject to capital accumulation in the entire economy (10), the resource constraint (2), and the balance of trade condition (11).

The corresponding Hamiltonian for maximizing W is

$$H = [\beta \log(q - x) + \log(px)] e^{-\rho t} + \lambda\left[\tilde{f}(L)k + a(t)n - (\omega + \theta)k - q\right] - \mu n e^{\theta t} \tag{13}$$

The resulting first-order conditions are

$$e^{-\rho t} \frac{\beta}{c} = \lambda \tag{14}$$

$$\frac{\beta}{c} = \frac{p}{z} \quad \text{or} \quad \frac{c}{\beta} = \frac{z}{p} = x \tag{15}$$

$$\lambda a(t) - \mu e^{\theta t} \begin{matrix} < \\ = \\ > \end{matrix} 0 \;\; \Rightarrow \;\; \begin{matrix} n = 0 \\ 0 < n < \bar{n} \\ n = \bar{n} \end{matrix} \tag{16}$$

$$\dot{\lambda} = \lambda\left[(\rho + \omega + \theta) - \tilde{f}(L)\right], \;\; \lambda(T) = \psi_T e^{-\rho t} \tag{17}$$

$$\dot{\mu} = 0, \; \mu \geq 0, \; F_0 - \int_0^T n e^{\theta t} dt \geq 0, \; \mu \left[F_0 - \int_0^T n e^{\theta t} dt \right] = 0 \tag{18}$$

plus the equation of motion (10).

Equation (14) is the usual condition requiring that the discounted marginal utility of consumption equals the shadow price of capital. Equation (15) is the open economy equilibrium condition, which indicates that the relative marginal value of domestic to imported consumption must equal the terms of trade, *p*. This condition can be re-written using (11) to indicate the marginal tradeoff between additional exports and domestic consumption in the economy.

Condition (16) governs the optimal rate of frontier resource extraction, *n*. The first term represents the benefit of extraction, $\lambda a(t)$. This is the marginal product of additional resource exploitation (see (6)) expressed in terms of the value of capital. In other words, any additional extraction and use of frontier resources has a potential for increasing valuable capital stock in the economy. However, the second term in (16), $\mu e^{\theta t}$, represents the user cost of exploitation; i.e., depletion today means less of the frontier resource available in the future for extraction and use. The latter cost consists of the scarcity value of the resource, μ, weighted by population growth, as larger future populations in the economy imply that greater resource extraction will be required in later periods. Condition (16) states that, if the value marginal product of frontier resource exploitation exceeds its marginal cost, then per capita resource extraction will be at the maximum rate, $\bar{n}$. If extraction costs are greater than the benefits, then no frontier resource exploitation will occur. When benefits equal costs, then extraction is at the rate *n* where $0 < n < \bar{n}$.

Equation (17) determines the change over time in the value of the capital stock of the economy. This value will grow if $\tilde{f}(L)$ is less than the effective discount rate plus any capital depreciation and population growth, $\rho + \omega + \theta$. In addition, the terminal value of the capital stock, $\lambda(T)$, combined with (14)-(16) will determine the final levels of per capita domestic consumption plus exports, $c(T) + x(T)$, in the economy.

Finally, condition (18) states that the marginal value, μ, of the fixed stock of frontier resources, F_0, is essentially unchanging over the planning horizon. Instead, whether the scarcity value of frontier resources is positive or zero depends on whether the available stock of frontier resources, F_0, is completely exhausted through extraction, *n*, by terminal time, *T*. Combined with the other first-order conditions, (18) proves to be important in characterizing the optimal "frontier resource exploitation" path of the economy.

For example, suppose that by the end of the planning horizon at time *T* the stock of frontier resources is not completely exhausted through "frontier exploitation", i.e. $F_0 > \int_0^T ne^{\theta t} dt$

over [0, T] such that $F(T) > 0$. From (18) it follows that $\mu = 0$. The unlimited availability of frontier resources to the economy over the entire planning period means that these reserves have no scarcity value. However, from (14), the marginal value of accumulated capital in the economy is always positive, $\lambda > 0$. As a consequence, leftover resource stocks imply that in (16) the value marginal product of frontier resource exploitation, $\lambda a(t)$, will exceed the costs, and thus the economy will exploit frontier resources at the maximum per capita rate, $\bar{n}$, throughout [0, T].

Alternatively, suppose that $F_0 = \int_0^T ne^{\theta t}dt$ so that frontier resources are exhausted at least by the end of the time horizon, T, if not at some time $t^F < T$. These resources now have positive scarcity value, $\mu > 0$, throughout the planning period. This in turn implies that optimal paths of frontier exploitation may have either an interior solution, $0 < n < \bar{n}$, or corner solutions, $n = \bar{n}$ and $n = 0$. Since these paths have interesting and differing economic implications, we will focus mainly on them. Thus the rest of the paper will consider only the case where frontier resource exploitation comes to an end some time during the planning horizon of the open economy.

We begin with the conditions for an interior solution to the choice of frontier resource extraction, $0 < n < \bar{n}$:

According to (12), an interior solution for n requires that the benefits of frontier exploitation equal the cost. This condition can be re-written as

$$\lambda = \frac{\mu e^{(\theta-\alpha)t}}{a_0} \quad \text{and} \quad \dot{\lambda} = (\theta - \alpha)\lambda \tag{19}$$

given that μ is constant. Substituting (19) into (17) yields

$$(\theta - \alpha)\lambda = \lambda[(\rho + \omega + \theta) - \tilde{f}(L)] \quad \text{or} \quad \tilde{f}(L) = \rho + \omega + \alpha\,. \tag{20}$$

The latter expression implies that $\tilde{f}'(L) = 0$, and from (8), that the marginal productivity of capital is constant, i.e. $\frac{\partial m}{\partial k} = \tilde{f}(L) = \rho + \omega + \alpha$.

Combining (11), (14), (15) and (17) yields

$$\begin{aligned} \dot{c} &= c\left[\tilde{f}(L) - (\rho + \omega + \theta)\right] \\ \dot{q} &= \dot{c} + \dot{x} = \left(1 + \frac{1}{\beta}\right)c\left[\tilde{f}(L) - (\rho + \omega + \theta)\right] \end{aligned} \tag{21}$$

Since $\widetilde{f}(L) = \rho + \omega + \alpha$, it follows that q and c will increase over time if $\alpha > \theta$, i.e. if exogenous resource technological change exceeds population growth in the economy. Thus, the interior solution for frontier resource extraction in this economy can be consistent with an optimal path leading to growth in per capita consumption and exports, provided that $\alpha > \theta$. If this is the case, which we will also assume throughout the rest of the paper, then frontier resource extraction under the interior solution will lead to the following growth conditions

$$g = \frac{\dot{q}}{q} = \frac{\dot{c}}{c} = \alpha - \theta \tag{22}$$

$$\dot{k} = a(t)n + (\rho + \alpha - \theta)k - q, \quad q(t) = q_0 e^{(\alpha-\theta)t}, \quad q(0) = q_0, \quad 0 < n < \overline{n}\,. \tag{23}$$

Growth in per capita consumption, exports and thus aggregate consumption, q, is therefore constant and equal to $\alpha - \theta$.[8] Because of the knowledge spillovers across firms, the marginal productivity of capital in the economy is constant but invariant with respect to capital per worker, k. In other words, there are no diminishing returns to capital in the economy, and thus as long as frontier resources can be exploited at the rate $0 < n < \overline{n}$, economic growth will occur at the constant rate $\alpha - \theta$.

The remaining two choices for the economy are the corner solutions $n = 0$ and $n = \overline{n}$. Both corner solutions yield the same dynamic equations (21) for q and c as the interior solution. It follows from (21) that, for both corner solutions to yield economic growth, requires $\widetilde{f}(L) > \rho + \omega + \theta$. Note as well that, since the labor force, L, is increasing over time, the average contribution of capital, $\widetilde{f}(L)$, will also rise over time. Thus the growth rate of the economy will increase due to this scale effect of population growth on the average contribution of capital to production. Consequently, the two corner solutions for frontier resource extraction will lead to the following growth conditions, respectively

$$g = \frac{\dot{q}}{q} = \frac{\dot{c}}{c} = \widetilde{f}(L) - (\rho + \omega + \theta) \tag{24}$$

$$\dot{k} = \widetilde{f}(L)k + a(t)\overline{n} - (\omega + \theta)k - q, \quad q(t) = q_0 e^{\int_0^t [\widetilde{f}(L) - (\rho+\omega+\theta)]dt}, \quad q_0 = q(0), \quad n = \overline{n} \tag{25}$$

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[8] In the remainder of the paper we will use the term "economic growth" as shorthand for growth in aggregate consumption, $q = x + c$.

$$\dot{k} = \tilde{f}(L)k - (\omega + \theta)k - q,\ q(t) = q_0 e^{\int_0^t [\tilde{f}(L) - (\rho + \omega + \theta)]dt},\ q_0 = q(0),\ n = 0 \tag{26}$$

Note that, just as both corner solutions differ in the rate of capital accumulation (compare (25) and (26)), they also differ in terms of the productivity of capital. For example, if frontier extraction is at the maximum rate, $n = \bar{n}$, the average and marginal productivity of capital are determined by (7) and (8). However, when frontier exploitation stops, $n = 0$, the average productivity of capital falls to equal the average contribution of capital, i.e. $m/k = \tilde{f}(L)$. Nevertheless, both the marginal and average productivity of capital remain invariant with respect to capital. Thus, once frontier resource extraction halts, the economy is no longer dependent on natural resource exploitation, but the "spillover" effects eliminate the tendency for diminishing returns as capital per worker accumulates, and growth can be sustained if condition (24) holds.

A final result of the model is that, if the economy is generating economic growth, it is never optimal to halt resource extraction as long as there is some frontier stock remaining. To see this, note that in the case of zero resource extraction, $n = 0$, positive growth also implies that the value of the value of the capital stock, λ, is positive but declining over time (see equations (24) and (17)).[9] From (16), halting frontier resource extraction will be an optimal choice only if $\lambda < \frac{\mu e^{(\theta-\alpha)t}}{a_0}$. However, from (18), $n = 0$ also requires $\mu F_0 = 0$ and $\mu \geq 0$, whereas (14) indicates that $\lambda(t) > 0$ always. Together, these conditions imply that the zero extraction policy is only optimal once the frontier resource stock is completely exhausted, i.e. when $F_0 = 0$.

To summarize, as long as some of the frontier resource is available and its exploitation generates economic growth, it is always optimal to exploit it. Frontier resource extraction will only be halted once the resource is completely exhausted. If frontier resource exploitation occurs at the maximum rate, then economic growth can be sustained provided that the average contribution of capital exceeds the sum of population growth, capital depreciation and the discount rate. If frontier exploitation occurs at less than the maximum rate, economic growth can also be sustained at a constant rate, equal to the difference between technological change in resource use and population growth. Once the frontier resource is completely exhausted, growth can still be sustained. Although the economy is no longer dependent on the resource for

[9] In fact, for all three solutions to generate economic growth results in a positive but declining value of the capital stock, λ.

production, knowledge spillovers eliminate the tendency for diminishing returns from accumulation of capital per worker and can therefore allow growth to continue indefinitely.

Equilibrium in the Decentralized Economy

A key issue is whether a social planner is necessary to achieve the optimal growth rates in the economy for aggregate consumption depicted in the previous section. In other words, in the absence of a social planner, will the equilibrium growth rates for q chosen through the decentralized decisions of individual consumers and producers also yield the optimal growth rates?

The decentralized outcome can be found by assuming that the representative infinite-lived household seeks to maximize overall utility over the time period $[0,T]$, given by

$$U = \int_0^T [\beta \log(c) + \log(z)] e^{-\rho t} dt + \psi_T s(T) e^{-\rho T}, \;\; \rho = \delta - \theta, \; \beta > 0, \tag{27}$$

subject to the household budget constraint (9), the resource constraint (2), and the balance of trade condition (11). From this maximization problem, the key conditions governing economic growth in the economy are

$$\lambda w^N \begin{matrix} < \\ = \\ > \end{matrix} \lambda a(t) = \mu e^{\theta t} \quad \Rightarrow \quad \begin{matrix} n = 0 \\ 0 < n < \bar{n} \\ n = \bar{n} \end{matrix} \tag{28}$$

$$\tilde{g} = \frac{\dot{q}}{q} = \frac{\dot{c}}{c} = [r - \theta - \rho] = \left[\tilde{f}(L) - L\tilde{f}'(L) - (\rho + \omega + \theta)\right], \tag{29}$$

where we make use of the conditions for the marginal products of resource use and capital (see (6) and (8)). We denote the decentralized growth rate as $\tilde{g}$ in order to distinguish it from socially optimal growth, g. It is clear from (29) that what determines the growth rate of aggregate consumption in the decentralized solution is the magnitude of the marginal product of capital, $\tilde{f}(L) - L\tilde{f}'(L)$.

However, it is easy to see that for the interior solution, $0 < n < \bar{n}$, growth condition (29) reduces to $\tilde{g} = -\dot{\lambda}/\lambda = \alpha - \theta$. Comparing the latter expression to (22), it appears that the decentralized and socially optimal growth rates are the same, i.e. $\tilde{g} = g$. That is, as long as the economy is pursuing a path in which some frontier expansion occurs but at a rate less than the maximum, the decentralized decisions of individual consumers and producers will yield socially optimal growth in aggregate consumption. In both the decentralized and optimal solutions, growth in aggregate consumption is constant and is determined by the difference between resource technological change and population growth.

In the case of the two corner solutions, $n = 0$ and $n = \bar{n}$, the decentralized growth rate is determined by (29). Comparing the latter to (24), it is clear that $\tilde{g} < g$. When the economy is either extracting resources at the maximum rate, $n = \bar{n}$, or when the frontier is closed, $n = 0$, the decentralized growth rate is lower than the planner's growth rate. This occurs because the presence of economy-wide knowledge spillover means that the private return to capital investment is lower than the social return. Unlike any social planner, individual producers do not internalize the knowledge spillovers, and so the decentralized growth rate (29) is set in accordance with the private marginal product of capital, $\tilde{f}(L) - L\tilde{f}'(L)$, which is less than the average contribution of capital in production, $\tilde{f}(L)$. In contrast, a social planner will take into account the spillovers, and the average contribution of capital is the determinant of the socially optimal growth rate in (24).[10]

However, the social optimum could be attained in a decentralized economy if the government chooses to subsidize the contribution of capital to firm's production. Such a subsidy would raise the private return to capital, thus eliminating the difference between social and private returns. To illustrate this, let's assume that the function for the contribution of capital to mainstay production takes the following Cobb-Douglas form, $f(k_i, K) = \gamma k_i^{\eta} K^{1-\eta}, 0 < \eta < 1$. It follows that a subsidy to each producer of $(1 - \eta)/\eta$ on the average contribution of capital would result in the following outcome in the decentralized economy

$$
\begin{aligned}
m_i &= a(t)n_i + \left(1 + \frac{1}{\eta}\right) f(k_i, K) = a(t)n_i + \frac{1}{\eta}\gamma k_i^{\eta} K^{1-\eta} \\
\frac{\partial m_i}{\partial k_i} &= \frac{1}{\eta} f_1(k_i, K) = \gamma \left(\frac{K}{k_i}\right)^{1-\eta} = \gamma L^{1-\eta} = \tilde{f}(L)
\end{aligned}
\tag{30}
$$

Thus the effect of the subsidy is to ensure that the private marginal product of capital in the economy equals the average contribution of capital. From (29), it is easy to see that the

[10] Note that, in the case of the interior solution, we proved that the private marginal product of capital is constant and equal to the average contribution of capital in the economy. Thus, there is no difference between the social and private returns to capital investment, and the decentralized and socially optimal growth rates are the same.

growth rate in aggregate consumption produced by the decentralized decisions of individual producers and consumers now equals the socially optimal rate of growth

$$\tilde{g} = \left[\tilde{f}(L) - (\rho + \omega + \theta)\right] = g \tag{31}$$

In sum, provided that the economy is exploiting frontier resources at less than the maximum rate, $0 < n < \bar{n}$, the equilibrium growth rate for aggregate consumption chosen through the decentralized decisions of individual consumers and producers will also yield the optimal growth rate. Any economic growth will be constant and equal to the difference between resource technological change and population growth. This result occurs because, despite the presence of knowledge spillovers in the economy, they are not influencing the optimal growth rate and so there is no difference between the social and private returns to capital investment. In contrast, if frontier resources are exploited at the maximum rate, $n = \bar{n}$, or when the frontier is closed, $n = 0$, the decentralized growth rate is lower than the planner's growth rate. In the latter cases, the presence of economy-wide knowledge spillovers does ensure that the private return to capital investment is lower than the social return. However, the difference between social and private returns to capital in the economy could be eliminated if the government chooses to subsidize the contribution of capital to firms' production. Such a policy would then enable the growth rate generated by the decentralized economy to be socially optimal.

Conclusion

Following recent studies of successful mineral-based development, we have demonstrated that under certain conditions frontier expansion in a small open economy can be associated with sustained growth. These conditions include: 1) resource-enhancing technological change; 2) strong linkages between the resource and manufacturing sectors; and 3) substantial knowledge spillovers across producers in the economy. These conditions are incorporated into a small open economy model by assuming that output produced through exploiting frontier "reserves" is an intermediate input into all manufacturing and industrial processing activities, capital accumulation by each firm engaged in the latter activities leads to knowledge spillovers across the entire sector, and exogenous technological change increases the effective stock of resources extracted available as intermediate inputs.

Our model leads to several important results in terms of optimal frontier resource exploitation and economic growth.

First, as long as some frontier resource is available, it is always optimal for the economy to extract and use the resource. If optimal extraction occurs at the maximum rate possible, then economic growth can be sustained provided that the average contribution of capital exceeds the sum of population growth, capital depreciation and the discount rate. Because any social planner will take into account the presence of knowledge spillovers, the average contribution of capital represents the social return to capital in the economy and thus determines the socially optimal growth rate. In contrast, if optimal frontier resource exploitation occurs at less than the maximum rate, then economic growth can also be sustained. However, in this case, any growth will be constant and equal to the difference between resource technological change and population growth. Although knowledge spillovers are still present in the economy, they do not affect the optimal growth rate.

Second, once the frontier is "closed" and all resource extraction stops, it is still possible to generate sustained growth in the small open economy. Although the economy is no longer dependent on the resource for production, knowledge spillovers eliminate the tendency for diminishing returns from accumulation of capital per worker and can therefore allow growth to continue indefinitely. The average contribution of capital once again represents the social return to capital, and thus determines the socially optimal growth rate. Moreover, since the labor force, L, is increasing over time, the average contribution of capital, $\tilde{f}(L)$, will also rise over time. Thus the growth rate of the economy will increase due to this scale effect of population growth on the average contribution of capital to production. In essence, the economy has transitioned from a frontier resource-dependent economy to a fully "modernized" capital-labor economy with knowledge spillovers leading to endogenous growth (Arrow 1962; Romer 1986). Thus the three conditions explored in the model of this paper appear to allow a small open economy to escape the "boom and bust" trap associated with frontier-based expansion (Barbier 2005).

Third, we also examined whether it is necessary for producers to receive a subsidy in order for the decentralized economy to attain the socially optimal growth rate. Such a subsidy is not necessary if the economy is exploiting frontier resources at less than the maximum rate. In this case, despite the presence of knowledge spillovers in the economy, there is no difference between the social and private returns to capital investment. In contrast, if frontier resources are exploited at the maximum rate or when the frontier is closed, a subsidy is necessary because the presence of an economy-wide knowledge spillover means that the private return to capital investment is lower than the social return. In the latter two cases, if the government subsidizes the contribution of capital to firms' production, the difference between social and private returns to capital in the economy could be eliminated, and the growth rate generated by the decentralized economy would also be socially optimal.

There is evidence from past examples of successful resource-based development that government subsidies, or at least complementary public investment, have played a pivotal role in generating the economy-wide increasing returns from such development (David and Wright 1997; Romer 1996; Wright and Czelusta 2002). For example, in explaining the world-wide ascendancy of the US copper industry during the 1880-1920 era, David and Wright (1997, p. 239) maintain that: "Capital requirements and long term horizons made copper an industry for corporate giants….These large enterprises internalized many of the complementarities and spillovers in copper technology, but they also drew extensively on national infrastructural investments in geological knowledge and in the training of mining engineers and metallurgists."

With regard to resource-based development today, there is unfortunately plenty of evidence that government investment and subsidies in resource sectors are not aimed at promoting knowledge spillovers but encouraging problems of rent-seeking and corruption, including in mineral-based economies (Ascher 1999; Barbier 2003 and 2004; Karl 1997; López 2003). Such policies not only dissipate resource rents and mitigate against efficient management of natural resources, but also ensure that whatever rents are being generated are not being channeled into productive investments elsewhere in the economy. As the model of this paper also suggests, a second consequence of such misallocation of government investments and subsidies is that the private returns to investment in the resource-based economy will fall short of the social returns. The result is that private firms will under-invest in resource-based production, thus leading to lower economic growth.

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